ECE 371
Materials and Devices

11/12/19 - Lecture 21

pn Junction Forward Bias

General Information

- Homework 6 solutions posted
- Homework 7 assigned and due Thursday 11/21
- Midterm 2 solutions posted
- If there are midterm grading questions, please follow this process:
    1. Review my solutions to compare your response to what I was looking for.
    2. If reviewing the solutions does not resolve your grading question, please see Hasan.
    3. If grading questions still cannot be resolved with Hasan, please see me.
- Reading for next time: 7.4 and 8.1

Biased pn Junctions

- No current due to potential barrier
- E is all built in to junction

- Potential barrier increases
- Still no current
- E increases
- Fermi levels separate

- Potential barrier decreases
- E decreases
- Electrons and holes diffuse across junction
- Current flows

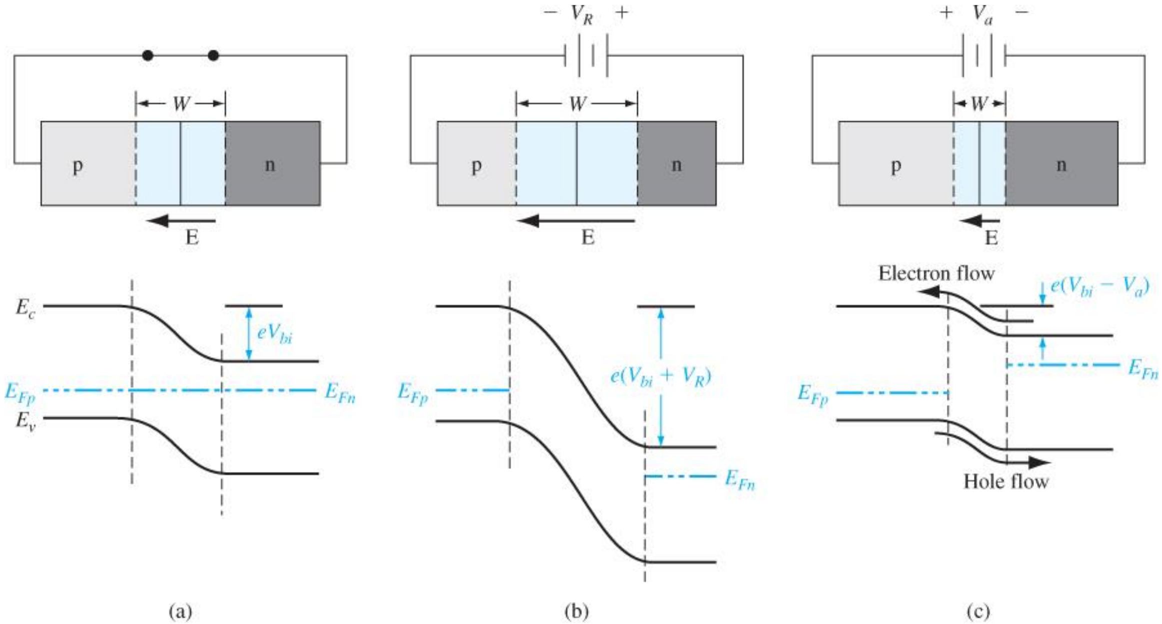


Figure 8.1 | A pn junction and its associated energy-band diagram for (a) zero bias, (b) reverse bias, and (c) forward bias.

Common Notation for Ch. 8

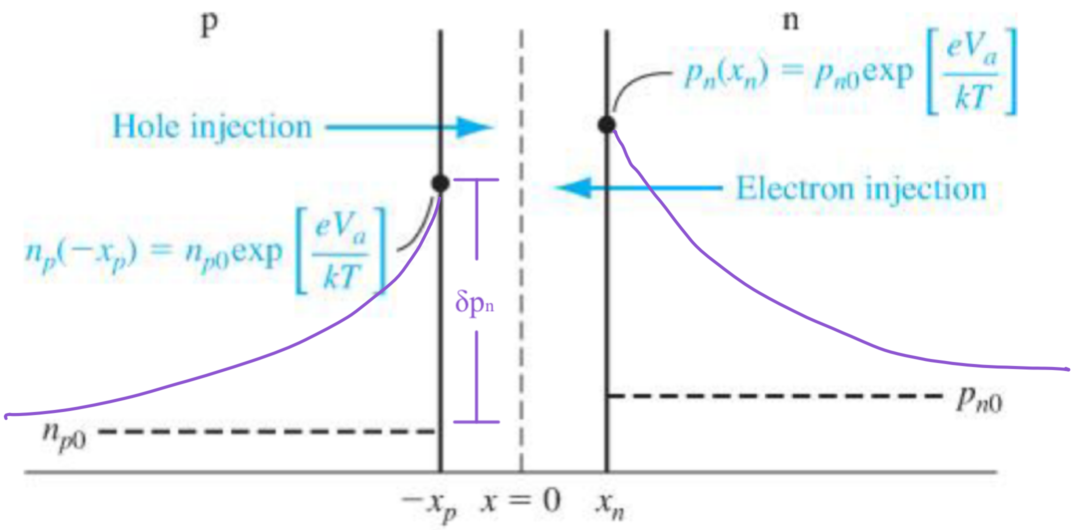
Table 8.1 | Commonly used terms and notation for this chapter

Term	Meaning
N_a	Acceptor concentration in the p region of the pn junction
N_d	Donor concentration in the n region of the pn junction
$n_{n0} = N_d$	Thermal-equilibrium majority carrier electron concentration in the n region
$p_{p0} = N_a$	Thermal-equilibrium majority carrier hole concentration in the p region
$n_{p0} = n_i^2/N_a$	Thermal-equilibrium minority carrier electron concentration in the p region
$p_{n0} = n_i^2/N_d$	Thermal-equilibrium minority carrier hole concentration in the n region
n_p	Total minority carrier electron concentration in the p region
p_n	Total minority carrier hole concentration in the n region
$n_p(-x_p)$	Minority carrier electron concentration in the p region at the space charge edge
$p_n(x_n)$	Minority carrier hole concentration in the n region at the space charge edge
$\delta n_p = n_p - n_{p0}$	Excess minority carrier electron concentration in the p region
$\delta p_n = p_n - p_{n0}$	Excess minority carrier hole concentration in the n region

Excess carriers

total

equilibrium



How to find $n_p(-x_p)$ and $p_n(x_n)$?

$$V_{bi} = \frac{KT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right) \longrightarrow \frac{n_i^2}{N_a N_d} = \exp\left(-\frac{eV_{bi}}{KT}\right)$$

(n-side) $N_d \approx n_{n_0}$ (p-side) $N_a \approx P_{p_0}$

and $P_{p_0} \cdot n_{p_0} = n_i^2 \longrightarrow n_{p_0} = \frac{n_i^2}{N_a}$

Relating N_{n_0} to n_{p_0} & P_{p_0} to p_{n_0}

$$n_{p_0} = n_{n_0} \exp\left(\frac{-eV_{bi}}{KT}\right)$$

$$p_{n_0} = p_{p_0} \exp\left(\quad \right)$$

If biased (foward) $V_{bi} \rightarrow V_{bi} - V_a$

foward bias

$$n_p = n_{n_0} \exp\left(\frac{-e(V_{bi} - V_a)}{kT}\right)$$

dropping o because not in thermal equib.

$$n_p = n_{p0} \exp\left(\frac{eV_a}{kT}\right) = n_p(-x_p)$$

Relating N_{p_0} to $n_p(-x_p)$

$p_n =$

$$p_n = p_{n_0} \exp\left(\frac{eV_a}{kT}\right)$$

Current across the junction is minority carrier & diffusion-based

Drift $J \propto nE$ so even though field is small, the number of carriers is huge, therefore some will drift

Assumptions

- The derivation of the ideal diode current-voltage characteristics assumes
  1. The junction is abrupt and the semiconductor is neutral outside of the depletion region.
  2. Maxwell-Boltzmann approximation applies
  3. Complete ionization and low-level injection apply
  4. The total current is constant throughout the entire pn structure
  5. The individual electron and hole currents are continuous functions through the pn structure
  6. The individual electron and hole current are constant through the depletion region — no recombination in junction
     not really accurate, but will be covered in 471

Low-Level Injection

- Applied bias injects excess electrons and holes into the material

total carrier concentrations

$$\boxed{n = n_0 + \delta n}$$

$$\boxed{p = p_0 + \delta p}$$

excess carrier concentrations

thermal equilibrium carrier concentrations

- Low-level injection is when the excess carrier concentration is much smaller than the thermal equilibrium majority carrier concentration

$$\boxed{\delta n \ll n_0}$$

$$\boxed{\delta p \ll p_0}$$

pn Junction - Forward Bias

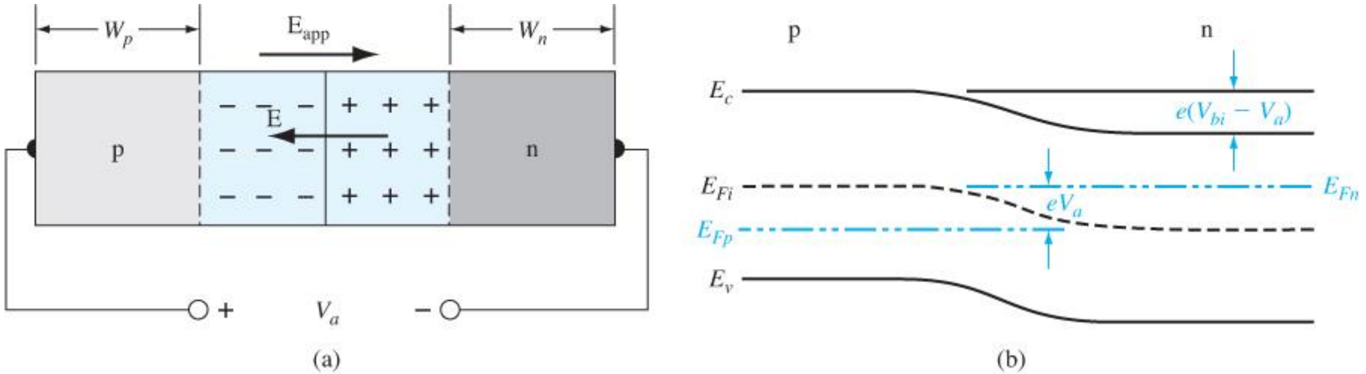


Figure 8.3 | (a) A pn junction with an applied forward-bias voltage showing the directions of the electric field induced by V_a and the space charge electric field. (b) Energy-band diagram of the forward-biased pn junction.

- Positive bias reduces potential barrier ($V_{bi} \rightarrow V_{bi} - V_a$)
- All applied bias is assumed to drop across depletion region
- E_{app} and E_{bi} are in opposite directions (total E is reduced)
- No longer have the drift/diffusion balance we had in thermal equilibrium
- Electrons and holes diffuse across the depletion region and produce a current as long as the applied bias continues

Minority Carrier Concentrations With Applied Bias

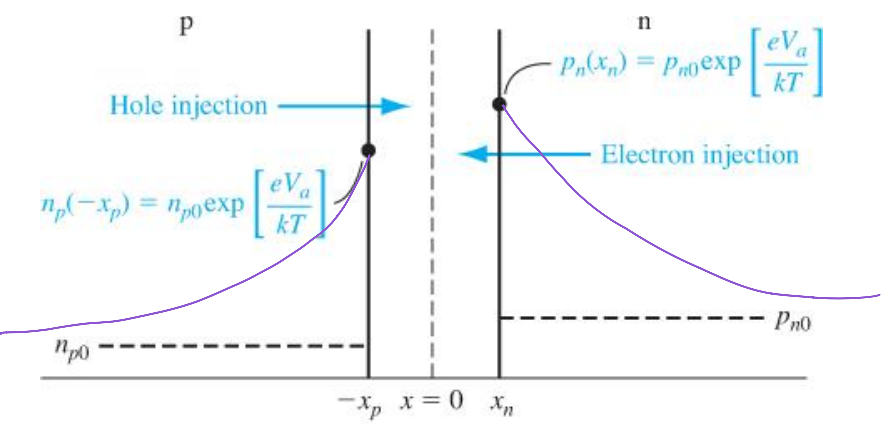


Figure 8.4 | Excess minority carrier concentrations at the space charge edges generated by the forward-bias voltage.

Total non-thermal equilibrium minority carrier concentrations at the depletion region edges

$$\boxed{n_p = n_p(-x_p) = n_{p_0} exp\left(\frac{eV_a}{kT}\right)}$$

$$\boxed{p_n = p_n(x_n) = p_{n_0} exp\left(\frac{eV_a}{kT}\right)}$$

- pn junction current is diffusion-based
- Holes inject into the n-side and electrons inject into the p-side
- Minority carrier concentrations can increase by many orders of magnitude under forward bias
- Majority carrier concentrations remain nearly constant under low-level injection
- Minority carrier concentrations are maximum at the depletion region edges and decay away from the edges due to diffusion and recombination

Ex. 8.1 Calculate the minority concentration at the edge of the depletion region.

$N_a = 10^{16}$ Si pn junct.

$N_d = 6 \times 10^{15}$ $T = 300K$

$V_a = 0.6V$

Find $n_p(-x_p)$ & $p_n(x_n)$

$$p_n(x_n) = p_{n_0} \exp\left(\frac{eV_a}{kT}\right)$$

majority is just the doping (100% ionization)

$n_{p_0} \cdot p_{p_0} = n_i^2$ $\qquad p_{p_0} = N_a \Rightarrow n_{p_0} = \frac{n_i^2}{N_a}$

$= 3.75 \times 10^4$

$N_{n_0} = N_d \Rightarrow p_{n_0} = \frac{n_i^2}{N_d}$

$= 2.25 \times 10^4$

$$p_n(x_n) = 2.25 \times 10^4 \exp\left(\frac{0.6}{0.0259}\right) = 4.3 \times 10^{14}$$ (10 orders of magnitude higher)

Transport Equations (from Ch. 6)

- The ambipolar transport equations describe the behavior of minority carriers as a function of space and time (Ch. 6) (Eq. 6.56 & B.B)

only left with diffusion & recombination

$$\boxed{D_n \frac{\partial^2(\delta n_p)}{\partial x^2} + \mu_n E \frac{\partial(\delta n_p)}{\partial x} + g' - \frac{\delta n_p}{\tau_{n0}} = \frac{\partial(\delta n_p)}{\partial t}}$$

*electrons in p-region

excess

$$\boxed{D_p \frac{\partial^2(\delta p_n)}{\partial x^2} - \mu_p E \frac{\partial(\delta p_n)}{\partial x} + g' - \frac{\delta p_n}{\tau_{p0}} = \frac{\partial(\delta p_n)}{\partial t}}$$

*holes in n-region

diffusion

opposite subscripts

drift

generation

recombination

change in time

$\delta_n = n_p - n_{p0}$

$\delta_p = p_n - p_{n0}$

dependence of

- g' = generation rate of excess carriers [#/(cm^3 s)]
- τ = minority carrier lifetime under low-level injection

Transport Equations (from Ch. 6)

- The transport equations can be simplified with the following assumptions
  1. The electric field is approximately zero in the quasi-neutral regions*
  2. The system is in steady state (e.g., $\frac{\partial(\delta n_p)}{\partial t} = 0$)
  3. There is no generation in the quasi-neutral regions or the depletion region. Generation only occurs right at the contacts.

$$\boxed{\frac{d^2(\delta n_p)}{dx^2} - \frac{\delta n_p}{L_n^2} = 0}$$

*electrons in p-region ($x \le -x_p$)

$$\boxed{\frac{d^2(\delta p_n)}{dx^2} - \frac{\delta p_n}{L_p^2} = 0}$$

*holes in n-region ($x \ge x_n$)

- Retain diffusion and recombination terms only
- $L_n^2 = D_n \tau_{n0}$ and $L_p^2 = D_p \tau_{p0}$ are the minority carrier diffusion lengths

*Actually, it is not exactly zero, just small, and is needed to supply drift of majority carriers to replenish the majority carriers that diffuse to the opposite side of the junction or recombine with injected minority carriers

Minority Carrier Distributions

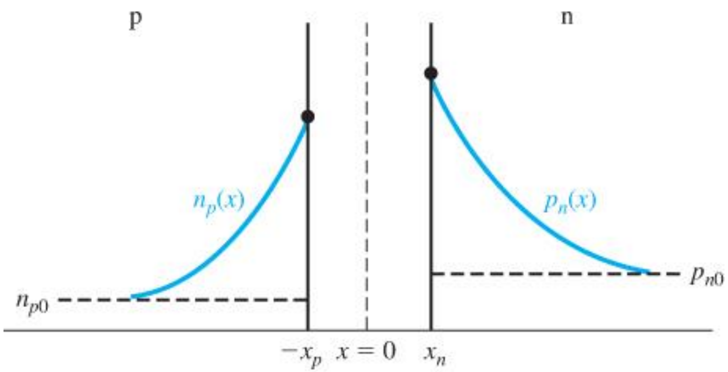


Figure 8.5 | Steady-state minority carrier concentrations in a pn junction under forward bias.

$$\boxed{\delta p_n(x) = p_{n0}\left[exp\left(\frac{eV_a}{kT}\right) - 1\right] exp\left[\frac{x_n - x}{L_p}\right]}$$

$$(x \geq x_n)$$

$$\boxed{\delta n_p(x) = n_{p0}\left[exp\left(\frac{eV_a}{kT}\right) - 1\right] exp\left[\frac{x_p + x}{L_p}\right]}$$

$$(x \leq -x_p)$$

- Majority carriers are injected across the junction and become minority carriers
- Minority carrier concentrations decay exponentially with distance from the junction edges back to their thermal equilibrium values
- Majority carrier concentrations are assumed to not deviate significantly from their thermal equilibrium values